

Long-term AGILE monitoring of the puzzling gamma-ray source 3EG J1835+5918

A. Bulgarelli¹, M. Tavani^{2,5}, P. Caraveo⁴, A.W. Chen^{3,4}, F. Gianotti¹, M. Trifoglio¹, M. Marelli⁴, A. Argan², G. Barbiellini⁶, F. Boffelli^{9,15}, P. W. Cattaneo⁹, V. Cocco², E. Costa¹, F. D'Ammando^{2,5}, E. Del Monte², G. De Paris², G. Di Cocco¹, I. Donnarumma², Y. Evangelista², M. Feroci², M. Fiorini⁴, T. Froyland^{2,5}, F. Fuschino³, M. Galli⁷, A. Giuliani⁴, C. Labanti¹, I. Lapshov², F. Lazzarotto², P. Lipari⁸, F. Longo⁶, M. Marisaldi¹, S. Mereghetti⁴, A. Morselli¹⁰, L. Pacciani², A. Pellizzoni⁴, F. Perotti⁴, G. Piano^{2,5}, P. Picozza^{5,10}, M. Prest¹¹, G. Pucella², M. Rapisarda¹², A. Rappoldi⁹, P. Soffitta², A. Trois², E. Vallazza⁶, S. Vercellone⁴, V. Vittorini^{2,3}, A. Zambra⁴, D. Zanello⁸, P. Giommi¹³, C. Pittori¹³, F. Verrecchia¹³, P. Santolamazza¹³, D. Gasparrini¹³, S. Cutini¹³, S. Colafrancesco¹³, L. Salotti¹¹

¹INAF/IASF–Bologna, Via Gobetti 101, I-40129 Bologna, Italy

²INAF/IASF–Roma, Via del Fosso del Cavaliere 100, I-00133 Roma, Italy

³CIFS–Torino, Viale Settimio Severo 3, I-10133, Torino, Italy

⁴INAF/IASF–Milano, Via E. Bassini 15, I-20133 Milano, Italy

⁵Dip. di Fisica, Univ. “Tor Vergata”, Via della Ricerca Scientifica 1, I-00133 Roma, Italy

⁶Dip. di Fisica and INFN Trieste, Via Valerio 2, I-34127 Trieste, Italy

⁷ENEA–Bologna, Via Biancamano 2521, I-40059 Medicica (BO), Italy

⁸INFN–Roma “La Sapienza”, Piazzale A. Moro 2, I-00185 Roma, Italy

⁹INFN–Pavia, Via Bassi 6, I-27100 Pavia, Italy

¹⁰INFN–Roma “Tor Vergata”, Via della Ricerca Scientifica 1, I-00133 Roma, Italy

¹¹Dip. di Fisica, Univ. dell’Insubria, Via Valleggio 11, I-22100 Como, Italy

¹²ENEA–Roma, Via E. Fermi 45, I-00044 Frascati (Roma), Italy

¹³ASI–ASDC, Via G. Galilei, I-00044 Frascati (Roma), Italy

¹⁴ASI, Viale Liegi 26, I-00198 Roma, Italy

¹⁵Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Via Bassi 6, Pavia, I-27100, Italy

received; accepted

ABSTRACT

Context. We present the AGILE gamma-ray observations of the field containing the puzzling gamma-ray source 3EG J1835+5918. This source is one of the most remarkable unidentified EGRET sources.

Aims. An unprecedentedly long AGILE monitoring of this source yields important information on the positional error box, flux evolution, and spectrum.

Methods. 3EG J1835+5918 has been in the AGILE field of view several times in 2007 and 2008 for a total observing time of 138 days from 2007 Sept 04 to 2008 June 30 encompassing several weeks of continuous coverage.

Results. With an exposure time approximately twice that of EGRET, AGILE confirms the existence of a prominent gamma-ray source (AGL J1836+5926) at a position consistent with that of EGRET, although with a remarkably lower average flux value for photon energies greater than 100 MeV. A 5-day bin temporal analysis of the whole data set of AGL J1836+5926 shows some evidence for variability of the gamma-ray flux. The source spectrum between 100 MeV and 1 GeV can be fitted with a power law with photon index in the range 1.6–1.7, fully consistent with the EGRET value.

Conclusions. The faint X-ray source RX J1836.2+5925 that has been proposed as a possible counterpart of 3EG J1835+5918 is well within the AGILE error box. Future continuous monitoring (both by AGILE and GLAST) is needed to confirm the gamma-ray flux variability and to unveil the source origin, a subject that is currently being pursued through a multiwavelength search for counterparts.

Key words. gamma-rays: observation;

1. Introduction

The gamma-ray source 3EG J1835+5918 (also known as GEV J1835+5921 and GRO J1837+59) is one of the most puzzling high-energy sources in the sky, and it has been the subject of considerable interest since its discovery by EGRET (Nolan et al. 1994). This source was catalogued among the brightest high-latitude unidentified sources with an average

gamma-ray flux above 100 MeV of $\Phi_{EGRET} = (60 \pm 4) 10^{-8}$ photons $\text{cm}^{-2} \text{s}^{-1}$, and a hard gamma-ray spectrum of photon index $\gamma = 1.69 \pm 0.07$ (Hartman et al. 1999). Owing to the spectral hardness (similar to that of the Vela pulsar), the source flux near 1 GeV is expected to be about half of the Crab value. The EGRET error box is well-determined, resulting in an error radius of $8'$ at the 95% confidence level.

The source 3EG J1835+5918 is located 25° off the Galactic plane and therefore is not significantly affected by the Galactic diffuse gamma-ray emission. EGRET pointed at this high-

galactic latitude region several times (Hartman et al. 1999). The resulting position, gamma-ray lightcurve, variability, and spectrum have been discussed in several papers: (McLaughlin et al. 1996; Nolan et al. 1996; Reimer et al. 2001). The analysis of the whole EGRET dataset produces a gamma-ray flux database consistent with being constant (Hartman et al. 1999; Reimer et al. 2001). However, it is important to notice that a claim for variability of 3EG J1835+5918 was indicated by Nolan et al. (1996).

The relatively strong gamma-ray flux, the hard spectrum, and the lack of an obvious blazar counterpart in the EGRET error box of 3EG J1835+5918 spurred considerable interest from several observing groups. After extensive X-rays, radio, and optical coverage of the EGRET error box (Mirabal et al. 2000; Reimer et al. 2001; Totani et al. 2002; Halpern et al. 2002) the search for possible counterparts singled out RX J1836.2+5925, a relatively faint soft X-ray source with no radio or optical emission: a set of characteristics similar to those of middle-aged radio-quiet neutron stars (Caraveo et al. 1996). Thus, on the basis of the gamma-ray properties of 3EG J1835+5918, coupled with those of RX J1836.2+5925, the sources was named *the next Geminga* by (Halpern et al. 2002) owing to its Geminga-like phenomenology (Bignami and Caraveo 1996). A search for X-ray pulsation, with period values ranging from 1 ms to 10 s, yielded a 35% upper limit to the source-pulsed fraction (Halpern et al. 2007). In view of the much lower pulsed fractions measured for all known middle-aged neutron stars, such a result did not weaken this tentative identification.

Taking advantage of the AGILE unprecedented exposure gathered during the science verification phase and early pointings of the Cycle-1 program, in this Letter we are now able to assess the source characteristics anew. Section 2 describes the AGILE-GRID observations and main results, while their implications are discussed in Section 3.

2. The AGILE GRID observations of 3EG J1835+5918

The AGILE instrument (Tavani et al. 2008) is composed of three detectors: a Tungsten-Silicon Tracker (ST) (Barbiellini et al. 2002; Prest et al. 2003), with a large field of view (~ 2.5 sr), optimal time resolution and angular resolution, and good sensitivity; a Silicon-based X-ray detector, Super-AGILE (SA) (Feroci et al. 2007) for imaging in the energy range 18 keV - 60 keV and a CsI(Tl) Mini-Calorimeter (MCAL) (Labanti et al. 2006) that detects gamma-rays or particle energy depositions between 300 keV and 100 MeV. The ST and MCAL form the AGILE Gamma-Ray Imaging Detector (GRID) for observations in the gamma-ray energy range 30 MeV - 50 GeV. The instrument is completed by an anti-coincidence (AC) system (Perotti et al. 2006), made with plastic scintillator layers, for the rejection of charged particles, and by an efficient trigger logic for gamma-ray and X-ray data acquisition (Tavani et al. 2008).

Data analysis was performed with the BUILD 15 of the AGILE Standard Pipeline, publicly available at the ASI Data Center web site (<http://agile.asdc.asi.it/>). The data were produced starting from the Level-1 data. The events collected during the passage in the South-Atlantic Anomaly and the Earth albedo background were consistently rejected. The GRID event direction were reconstructed by a Kalman filter technique. To reduce the particle background contamination, we selected with the GRID filter FT3ab_2 only events flagged as confirmed γ -ray events (*G* class events, corresponding to a sensitive area of

$\sim 300 \text{ cm}^2$ at 100 MeV). All the fluxes reported in this Letter have been consistently checked and scaled with their corresponding errors using the ratio $R = \frac{\Phi(Vela)_{EGRET}}{\Phi(Vela)_{AGILE}}$ computed for similar off-axis angles, with $\Phi(Vela)$ the gamma-ray flux above 100 MeV reported by EGRET and measured by AGILE. Scaling our fluxes measured for 3EG J1835+5918 to the Vela PSR measurements by AGILE and EGRET also takes systematic effects into account (estimated to be of the order of the 10% of the fluxes reported here).

All AGILE observations of the field containing the 3EG J1835+5918 are listed in Table 1. The columns report the viewing periods name (as reported in the ASI Data Center web site), the galactic coordinates of the centre of the field of view, the start and end of the observation in UTC, the average source off-axis angle, the *period-averaged* flux F_γ ($E > 100 \text{ MeV}$) in photons $\text{cm}^{-2} \text{ s}^{-1}$ (if $\sqrt{TS} < 3$ a $2 - \sigma$ upper limit is reported), the $1 - \sigma$ statistical and systematic uncertainty of the flux, the number of counts, and in the last column the statistical significance of the likelihood ratio test.

AGILE counts, exposure, and galactic background maps were generated with a bin size of $0.25^\circ \times 0.25^\circ$ for $E > 100 \text{ MeV}$ to compute the source flux and its evolution, while maps with a bin size of $0.1^\circ \times 0.1^\circ$ were used to optimize the source position using a likelihood analysis method (Mattox et al. 1996a). Our analysis was performed over a region of 10° radius.

2.1. The gamma-ray source positioning

To determine the most likely location of the gamma-ray source, we used only the best viewing periods, i.e. those in which the source was within 50° from the instrument pointing direction. For $E > 100 \text{ MeV}$, the best position computed by the likelihood analysis is $l = 88.90^\circ$ $b = 24.99^\circ$, corresponding to $\alpha = 18^\circ 36' 20''.11$, $\delta = 59^\circ 26' 42''.3$. We name this source AGL J1836+5926. Figure 1 shows a Gaussian-smoothed counts map of the source with our 95% statistical and systematic error ellipse with semiaxis $a = 0.265^\circ$ and $b = 0.200^\circ$. To conservatively take both systematic and statistical effects into account, we obtain a 95% confidence level radius by linearly adding a systematic error of 0.1° to the 95% statistical error ellipse.

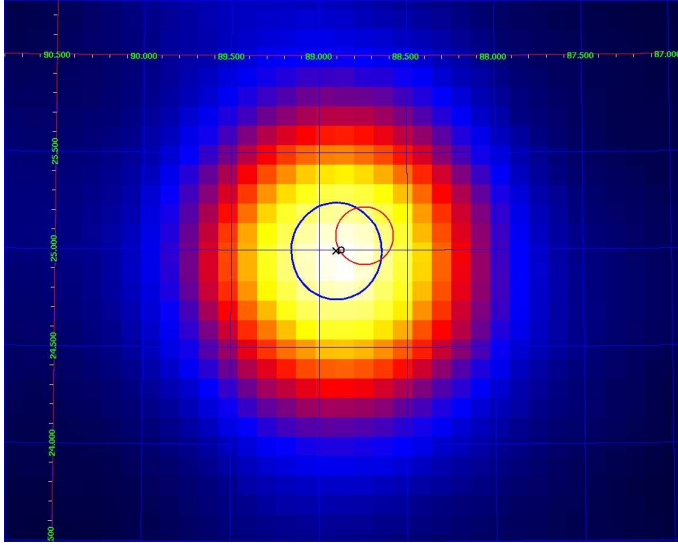
The AGILE 95% error ellipse is consistent with the error box of 3EG J1835+5918 (Mattox et al. 2001), and the distance between AGILE and EGRET centroids is $\sim 10.2'$. The distance between the position of the X-ray source RX J1836.2+5925 and the AGILE 95% maximum likelihood contour level barycentre is $\sim 1.4'$. The source detection significance, as derived from a maximum likelihood analysis, is $16.7\text{-}\sigma$. A total of 499 photons with $E > 100 \text{ MeV}$ have been collected. The source flux, averaged over the whole AGILE dataset, is $\Phi_{AGILE} = (38.7 \pm 3.0) \times 10^{-8} \text{ photons cm}^{-2} \text{ s}^{-1}$, which turns out to be approximately 60% less than the value reported in the 3rd EGRET Catalogue.

2.2. The gamma-ray spectrum

Our standard GRID spectral analysis was performed using 3 energy bins, namely 100-200 MeV, 200-400 MeV, 400-1000 MeV. Photons below 100 MeV and above 1 GeV have not been used in the analysis reported here. The analysis was obtained by summing the observation periods OB5600, OB5700, and OB5800 (see Table 1). A power-law model fit to the data yields a photon index $\gamma = 1.65 \pm 0.22$.

Table 1. *AGILE observations of 3EG J1835+5918.*

Viewing period	l	b	Start (UTC)	End (UTC)	Off-axis angle	F_γ	ΔF_γ	Counts	\sqrt{TS}
OB2300	134.882	11.822	2007-09-04 12:00	2007-09-12 12:00	50	< 40		< 13	1.8
OB4610 + OB4630	143.365	41.588	2007-10-24 08:00	2007-11-01 12:00	50	81	18	37 ± 10	4.4
OB4800	69.594	4.623	2007-11-02 12:00	2007-12-01 12:00	27	40	6	99 ± 16	7.7
OB4900	88.815	9.928	2007-12-01 12:00	2007-12-05 09:00	15	39	14	18 ± 5	3.8
OB4910 + OB4920	85.119	-9.416	2007-12-05 09:00	2007-12-16 12:00	38	48	12	44 ± 10	5.2
OB5210	77.309	40.628	2008-02-09 09:00	2008-02-12 12:00	20	60	19	21 ± 7	4.2
OB5600	53.039	6.474	2008-04-10 12:00	2008-04-30 12:00	40	40	10	57 ± 13	5.0
OB5700	104.852	35.439	2008-04-30 12:00	2008-05-10 12:00	30	49	11	49 ± 10	6.2
OB5800	74.05	0.273	2008-05-10 12:00	2008-06-09 12:00	30	50	9	129 ± 18	9.6
OB5820	93.6	-1.16	2008-06-15 12:00	2008-06-30 12:00	30	25	8	37 ± 11	4.2

**Fig. 1.** *Gaussian-smoothed counts map with squared scale of AGL J1836+5926 with photons of $E > 100$ MeV. The red curve is the EGRET 95% error ellipse, the blue curve is the AGILE 95% statistical plus systematic error ellipse, the cross is the AGILE 95% error ellipse barycentre, and the black circle is the position of the X-ray source RX J1836.2+5925.*

2.3. The gamma-ray lightcurve and variability analysis

The search for the variability of the gamma-ray emission of 3EG J1835+5918 produced somewhat inconclusive results. Using the first EGRET viewing periods, McLaughlin et al. (1996) and Nolan et al. (1996) classified 3EG J1835+5918 as a possibly variable source. On the other hand, using the whole EGRET data set Reimer et al. (2001) and Nolan et al. (2003) did not confirm the previous hint of variability. (We note that none of the previous EGRET variability studies used the same 5-day intervals adopted in this Letter.)

To study the source temporal behaviour, each AGILE viewing period was first analysed to determine the parameters of the Galactic diffuse radiation model and of the isotropic diffuse intensity level. The source flux density was then estimated independently for each 5-day temporal bin with the gamma-ray model parameters fixed at the values obtained in the first step. Figure 2 shows the AGL J1836+5926 gamma-ray flux lightcurve during the period September 2007 to June 2008 for photons with $E > 100$ MeV.

We fit the AGILE GRID fluxes to a constant value (the weighted mean of the average flux values), and computed the V variability coefficient for the AGILE observations (McLaughlin et al. 1996). The $2\text{-}\sigma$ upper limits (UL) were properly treated, assigning a value and a σ equal to $UL/2$ (Torres et al. 2001a). A value of $V > 1$ is an indication of variability within the observing period. The AGILE observation block durations of Table 1 span a non-homogeneous range of timescales from 1 week to more than a month. To study the flux variability of AGL J1836+5926 on a timescale of a few days, we chose a temporal bin size of 5 days as a good compromise between statistics and variability characteristics. Using a 5-day bin size, we obtain $\chi^2 = 38.34$ for 24 degrees of freedom and a value of $V = 1.495$. We can exclude the flux being constant at the 96.80% level. For a temporal bin of 4 days we obtain $V \simeq 1$. For temporal bins of 3 days or shorter, there are too many upper limits during the whole exposure time. For temporal bins of more than 5 days, we obtain $V < 1$, as expected for averaging a signal potentially variable on a timescale of a few days.

We note that, during the long uninterrupted coverage obtained in Nov-Dec 2007 and in April-June 2008, the gamma-ray source AGL J1836+5926 was not detectable (failing to reach the $3\text{-}\sigma$ threshold) for about half of the observing time. We also determined hard X-ray upper limits for AGL J1836+5926 in the energy range 18-60 keV from an analysis of Super-AGILE data. A 3-sigma upper limit of 10 mCrab was obtained for the OB5700.

2.4. EGRET vs AGILE

After one year of operations, AGILE has doubled the EGRET exposure time of 3EG J1835+5918, confirming the source position and spectral shape and showing evidence of variability. A comparison of the AGILE and EGRET observations of 3EG J1835+5918 is reported in Table 2. With a few exceptions, the EGRET pointings were generally one-week long (Reimer et al. 2001), and they were not optimally suited to tracing an emission variable on week to month long timescales. On the other hand, AGL J1836+5926 has been continuously in the AGILE field of view for more than two months in April-June 2008, in addition to several weeks scattered between September 2007 and December 2007. It is too early to say whether the apparent variations are erratic or follow some kind of cyclic pattern. Longer, continuous exposures (both with AGILE and GLAST) are needed to clarify this crucial point.

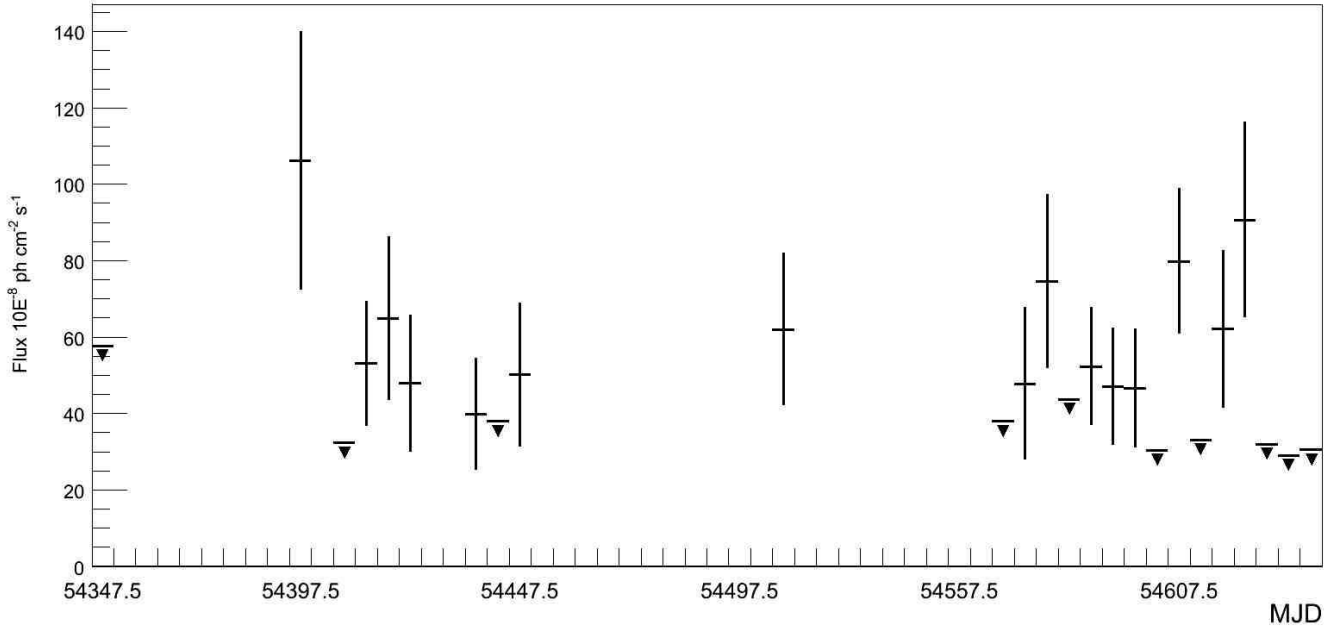


Fig. 2. AGILE gamma-ray light-curve of AGL J1836+5926 for photons above 100 MeV with a 5-day temporal bin.

Table 2. Comparison of total exposure and number of photons gathered by EGRET and AGILE from 3EG J1835+5918 for $E > 100$ MeV.

	$cm^2 s sr/0.5^\circ$ bin	Photons $E > 100$ MeV
EGRET	52900	452
AGILE	118325	499

3. Discussion and conclusions

The AGILE observations and monitoring of AGL J1836+5926 adds relevant information about this puzzling source. Postponing an account of our multifrequency observations of the region to a forthcoming paper, we briefly outline here a few important points regarding the search for a counterpart. We confirm a point already noticed by other authors, i.e., the absence of a blazar or any other relatively bright radio sources in the field containing the AGILE (and EGRET) error box. The analysis of Mattox et al. (2001) shows a 100 mJy source (B1834+5904) positioned at the 99.5% probability contour (12'.7 from the EGRET centroid position and 21'.8 from the AGILE centroid position). By using the NED, SIMBAD, and the Massaro et al. (2007) catalogues, we confirm the absence of a radio-loud blazar in the revised AGILE error box.

Outside this error box, we notice the existence of RGB J1841+591, a BL Lac type object positioned at 43'.5 from the AGILE centroid position. Even though occasional contributions from this object cannot be excluded in our analysis of AGILE, we emphasise that the AGILE integrated flux positioning at the 95% contour level is clearly not consistent with any substantial contribution from RGB J1841+591.

We also notice that the faint X-ray source RX J1836.2+5925 that was proposed as a possible counterpart is well within the AGILE error box of AGL J1836+5926. A hint of variability of this source was noticed when comparing two HRI ROSAT observations taken almost three years apart (Mirabal et al. 2001),

prompting a claim for the discovery of a new class of compact gamma-ray sources (Mirabal et al. 2000). However, subsequent Chandra X-ray observations showed a practically constant X-ray flux of RX J1836.2+5925, and weakened the variability claim in favour of a scenario encompassing a constant Geminga-like source.

We note here that our group observed the region containing RX J1836.2+5925 with the SWIFT XRT and XMM-Newton during the period May-June 2008. Analysis of these data and a full discussion of the AGL J1836+5926 counterpart problem will be presented elsewhere.

Future continuous monitoring (both by AGILE and GLAST) is needed to confirm the gamma-ray flux variability and to unveil the source origin.

References

- Barbiellini, G., et al. 2002, NIM A 490, 146-158;
- Bignami, F. B. and Caraveo, P. A., 1996, Ann. Rev. Astron. Astrophys., 34, 331-360
- Caraveo, P. A., Bignami, F. B., Trumper, E. T. 1996, A&A Review, 7, Number 3
- Feroci, M., et al. 2007, Nucl. Inst. and Meth. A, 581, 728-754
- Halpern, J. P., Wang, F. Y.-H. 1997, ApJ, 477, 905-915
- Halpern, J. P., et al. 2002, ApJ, 573, 41-44
- Halpern, J. P., Camilo, F., Gotthelf, E. V. 2007, ApJ, 668, 1154-1157
- Hartman R. C., et al. 1999, ApJ Supplement Series, 123, 79202
- Labanti, C., et al. 2006, Nuclear Physics B Proc. Suppl., 150, 34-37
- Massaro, E., et al. 2007, AIP Conf. Proc., 921, 349-350
- Mirabal, N., et al. 2000, ApJ, 541, 180-193
- Nolan, P. L., et al. 1994, Proc. 2nd Compton Symposium, Am. Inst. Phys. Conf. Proc. 304, Am. Inst. Phys., New York
- Nolan, P. L., et al. 1996, ApJ, 459, 100
- Nolan, P. L., et al. 2003, ApJ, 597, 615-627
- Mattox, J. R., et al. 1996, ApJ, 461, 396-407
- Mattox, J. R., Hartman, R. C., Reimer, O. 2001, ApJ, 135, 155175
- McLaughlin, M. A., et al. 1996, ApJ, 473, 763
- Mirabal, N., et al. 2001, ApJ, 547, 137-140
- Perotti, F., et al. 2006, Nucl. Inst. and Meth. A, 556, 228-236
- Prest, M., et al. 2003, Nucl. Inst. and Meth. A, 501, 280-287
- Reimer, O., et al., 2001, Mon. Not. R. Astron. Soc. 324, 772780

Tavani, M., et al. 2008, submitted to A&A , arXiv:0807.4254v1 [astro-ph]
Torres, D. F., Romero, G. E., Combi, J. A., et al. 2001, A&A , 370, 468
Totani, T., Kawasaki, W., Kawai, N. 2003, The Proceedings of the IAU 8th Asian-Pacific Regional Meeting, Volume I, ASP Conference Proceedings, Vol. 289